High Brightness Imaging for Real Time Measurement of Shock, Particle, and Combustion Fronts Produced By Enhanced Blast Explosives

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Abstract

High brightness imaging (HBI) has been used to study the structure of the leading shock, particles immediately behind the leading shock, and the following contact surface of combustion front (i.e., the "fireball") produced during testing of enhanced blast explosives (two kg main charge weight) in real time. These measurements are preliminary, as only six different explosives formulations were tested. However, results show that HBI can provide valuable information regarding the manner in which enhanced blast explosives differ from each other, and function in general. In particular, the high brightness imaging technique described here shows that some formulations produce particles ahead of the fireball, while others do not. Also, the distance between the leading shock and the fireball varies by formulation. Finally, for those formulations that produce particles in the space between the leading shock and the fireball, it appears that at later times the fireball expansion velocity (measured at the leading edge of the fireball) decelerates less than other formulations. For the six formulations tested thus far using HBI, we report leading shock velocities, leading shock thickness, particle images (or lack thereof), and fireball leading edge velocities.

1. Introduction

Understanding the function of enhanced blast explosives (EBX, also sometimes referred to as thermobaric explosives, TBX) depends upon knowledge of the physical structure of the blast event, especially the outermost region where interaction with ambient air occurs. This outermost region is believed to be composed of (in order of encounter) a leading shock, followed in some cases by metallic particles and other explosive-charge debris, followed by the contact surface of the combustion wave (the "fireball") [Lottero, 2004a]. For the work described here, a high brightness imaging (HBI) technique was used to provide real time measurements of the outermost region of the blast event.

2. Experimental

The HBI technique employs a high powered, high repetition rate (5-12 kHz) copper vapor laser (510 nm, Oxford Lasers, Inc.) synchronized to a filtered high speed digital camera (Vision Research, Inc.). The laser illuminates the fireball with light that is usually much brighter, over the wavelength range of the light emitted by the laser (510 nm), than light emitted by the fireball. The laser energy is typically near 1 milliJoule per pulse, beam diameter at the exit port of the laser (prior to beam expansion) of approximately 4 cm, nominal pulse length of 10 nanoseconds, at a repetition rate of 12 kHz, for an average power near 12 Watts. Emission from an explosive event at early times (~ 500 microseconds) is typically bright enough to saturate most cameras. Filtering or reducing the light reaching the camera at early times can provide images near the initiation time, but at the cost of later time events where the available light is reduced. The high brightness imaging technique used by us combines filtering of the light reaching the camera (notch filter near 510 nm, notch width approximately 10 nm) with illumination of the target by a laser emitting light at 510 nm. Additionally, the camera shutter is synchronized to the laser emission so that the laser only fires when the camera shutter is open (shutter open time of 10 microseconds). For the experiments reported here, a sheet of highly reflective material was placed approximately 3 meters behind the fireball location, so the lens-expanded laser beam shone light through the edge of the fireball, illuminating the sheet of reflective material behind the fireball. The camera lens was then focused on the surface of the reflective material.

Figure 1 shows a schematic of the setup used for the HBI measurements. Figure 2 shows a detail of the experimental apparatus for HBI measurement of blast wave structure measurement, overlaid with early time images from one of the measurements reported here. A

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detailed description of the full blast facility, including the instrumented pipe and experimental protocol, has been published separately [Lottero, 2004b]. For measurements reported here, the high-speed camera was focused so that the entire area between explosive charge and the mouth of the instrumented capture pipe was imaged. However, only the area immediately in front of the opening of the instrumented pipe was illuminated by the copper vapor laser.

Figure 3 shows a sequence of high brightness images showing the progress of the blast wave towards the capture pipe, the image of the leading shock, and particles within the fireball immediately behind the leading shock, for an enhanced blast explosive. Figure 3a is an image taken prior to the experiment (same image as in Figure 2), laser off and high speed camera unfiltered, showing the 2 kg main-charge explosive formulation, mounted on a stand 2 meters above the ground plane (explosive is on the right side of the image). On the left side of Figure 3a is a 0.5 m^2 sheet of reflective material used to image the region immediately in front of the instrumented pipe used to measure explosive impulse. The leading edge of the instrumented pipe is also visible on the left side of Figure 3a. Figure 3b shows an image taken with the laser on (note the circular, illuminated region of the reflective material), the camera filter in place, 250 usec after explosive initiation. Figures 3c-3d show the explosive cloud traveling towards the instrumented pipe (note the decrease in luminosity of the fireball). Figure 3e shows the leading shock and fireball contact surface (particles within the fireball) traveling through the illuminated region. Leading shock velocity for most formulations, measured 2 milliseconds after explosive initiation, was typically near 650 m/s.

Most of the late time (time after detonation greater than approximately 250 microseconds) fireball emission is effectively eliminated by using a camera filtered and synchronized to see only light in the wavelength region of the laser. Stuctures normally hidden to conventional imaging techniques, i.e., structures *composing* the outer blast structure, are imaged in real time. To our knowledge, this is the first application of the high brightness imaging technique to the investigation of the leading shock and contact surface of the blast structure produced by enhanced blast explosives.

3. Results and Discussion

Table 1 lists the explosive formulations used for the HBI measurements. The first two explosive formulations listed in Table 1 (Comp B and Tritonal) are "conventional" high explosives [Meyer, 2002] composed mainly of the crystalline compounds trinitrotoluene (TNT) and trimethylene trinitramine (RDX). Aluminum particles are added to the TNT in Tritonal to increase blast temperature. Explosive formulations 3-6 in Table 1 are all enhanced blast explosive (EBX) formulations proprietary to the U.S. Government and/or government contractors, as appropriate. In general, these formulations contain a crystalline energetic material, a metal (Al in powder or flake form) and other solid or liquid fuel additives.

Figures 4-9 show HBI imaging data from measurements of explosive formulations listed in Table 1, showing shock and fireball leading edge positions as a function of time after initiation. Also shown in the inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

It is worth noting that for explosive formulations NC1 (Figure 6) and NC2 (Figure 7) the separation between leading shock edge and leading fireball edge is at a maximum for all explosive formulations tested. Also, in the inset images in Figures 6 and 7, there appear to be "clouds" of particles in the space between leading shock and fireball edges. These formulations (NC1 and NC2) were the only formulations tested that showed what appear to be clouds of particles between the leading edges of the shock and the fireball.

Figure 10 provides a comparison of shock and fireball velocities, and their separation, 2 milliseconds after initiation for the 6 explosive formulations. For each of the formulations tested, the velocity of the leading shock at 2 milliseconds after initiation is near 650 meters per second. The fireball velocity is the greatest for the formulations NC1, NC2, and TX1. Interestingly, the separation of shock leading edge and fireball leading edge is greatest for the

formulations NC1 and NC2. Because the leading shock is always ahead of the leading fireball edge, a reasonable explanation of this behavior is that the velocity of the fireball for the explosive formulations NC1 and NC2 is slowing down less than that of the other explosive formulations. We believe that this effect must be due to increased turbulent mixing within the fireball. While it is conceivable that the fireball velocity in formulations NC1 and NC2 is being augmented by encountering a shock heated mixture of particles and ambient air, we believe that observation of particles in the region between leading shock and leading fireball edge may be indicative of increased turbulent mixing within the fireball. This explanation is supported by experimental data, but further work is needed to verify increased mixing within the fireball volume.

4. Conclusion

Results from a series of high brightness imaging (HBI) measurements on several conventional and enhanced blast explosive formulations show significant differences in separation between leading edges of shock and fireball. For certain enhanced blast explosives, the gap between the leading shock and the fireball appears to contain small particles. For the formulations that show particles in the gap between leading shock and fireball, at 2 milliseconds after initiation, the fireball velocity and gap distance is up to twice as large as for other formulations. We believe that particles "pushed" ahead of the fireball is indicative of increased turbulent mixing within the fireball, augmenting the blast behavior. We believe this preliminary data provides insight into the function of enhanced blast explosives and shows the value of high brightness imaging for evaluating performance of these explosive formulations.

Acknowledgements

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Formulation Name	Composition	Weight
1. Comp B	RDX, TNT	2 kg
2. Tritonal	TNT, Al	2 kg
3. PX1	RDX, Al, proprietary	2 kg
4. TX1	RDX,Al, proprietary	2 kg
5. NC1	RDX, Al, liquid, proprietary	2 kg
6. NC2	RDX, Al, liquid, proprietary	2 kg

Table 1: Explosive formulations used for HBI measurements.

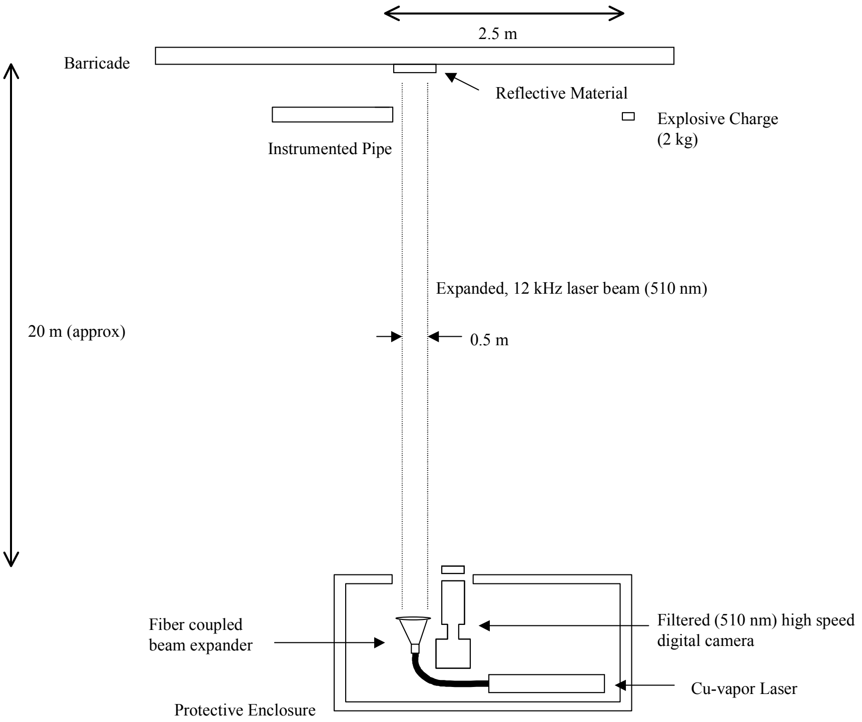

Figure 1: Schematic of the experimental apparatus used for the high brightness imaging measurements.

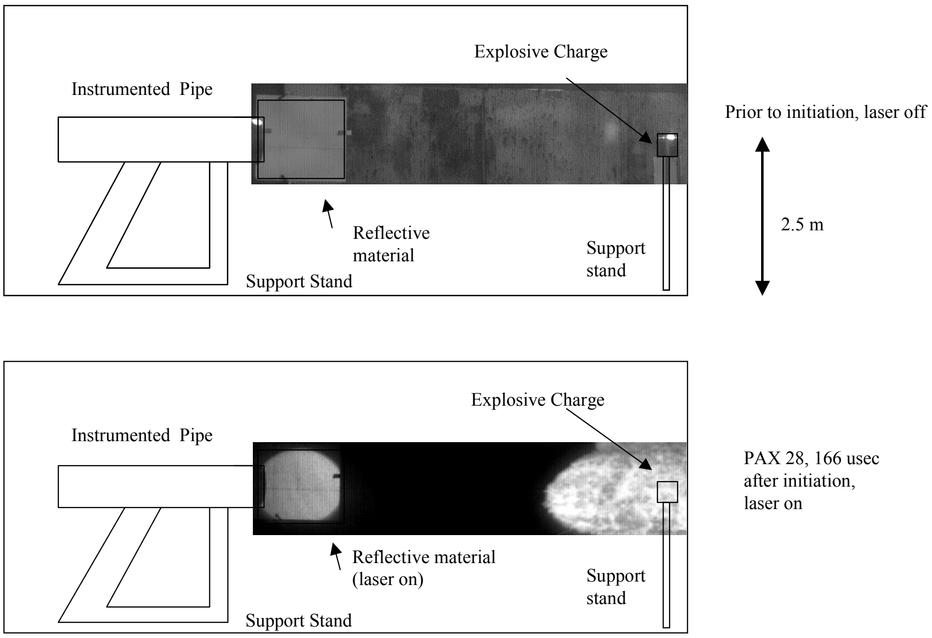

Figure 2: A detail of the experimental apparatus for HBI measurement of blast wave structure measurement, overlaid with early time images from one of the measurements reported here.

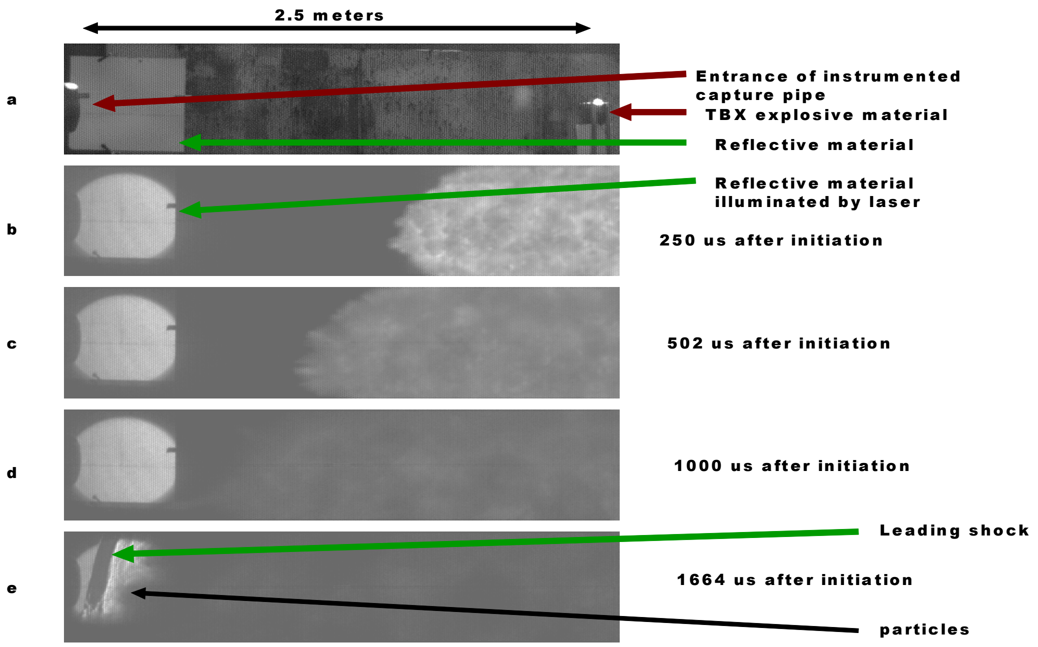

Figure 3: High brightness images following initiation of an enhanced blast explosive (referred to here as a TBX explosive material).

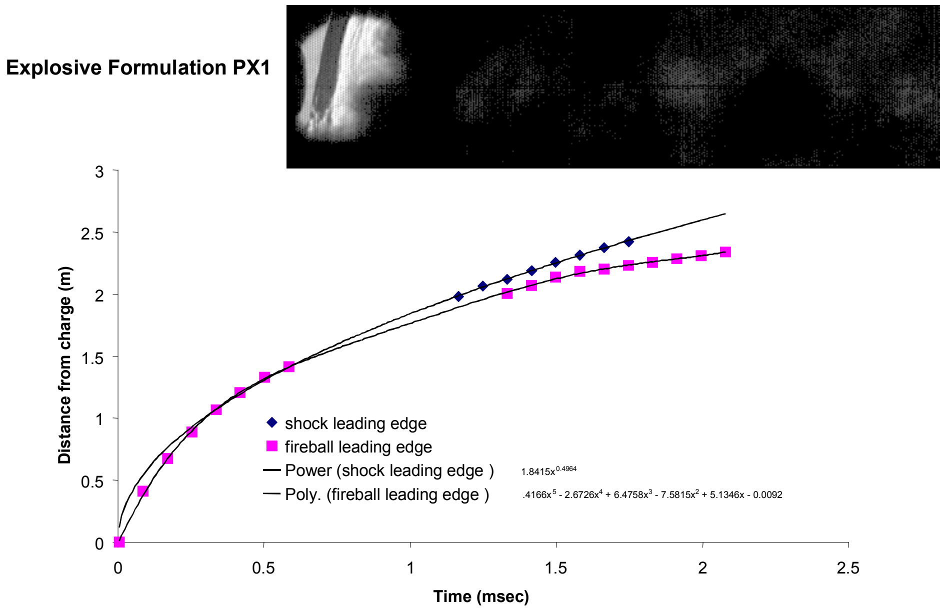

Figure 4: HBI imaging data from measurements of explosive formulation PX1, showing shock and fireball leading edges as a function of time after initiation. Also shown in inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

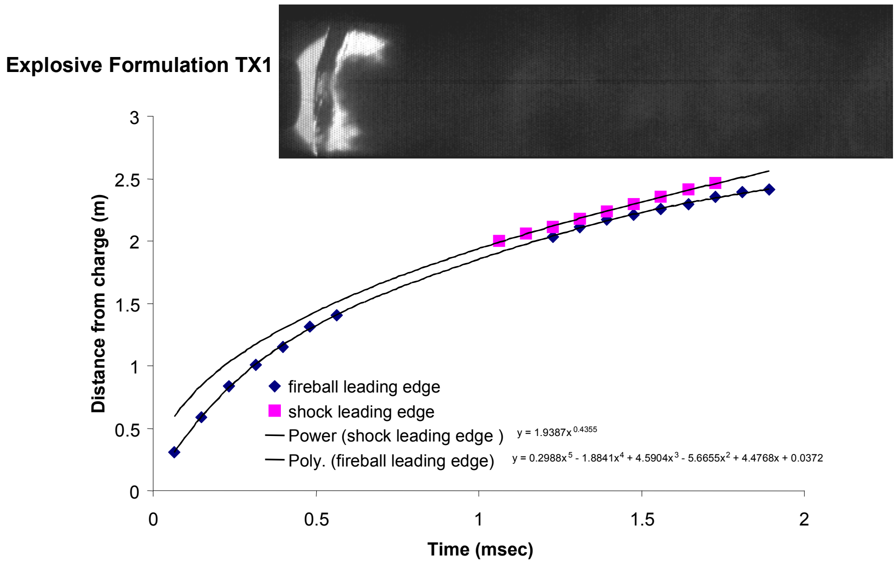

Figure 5: HBI imaging data from measurements of explosive formulation TX1, showing shock and fireball leading edges as a function of time after initiation. Also shown in inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

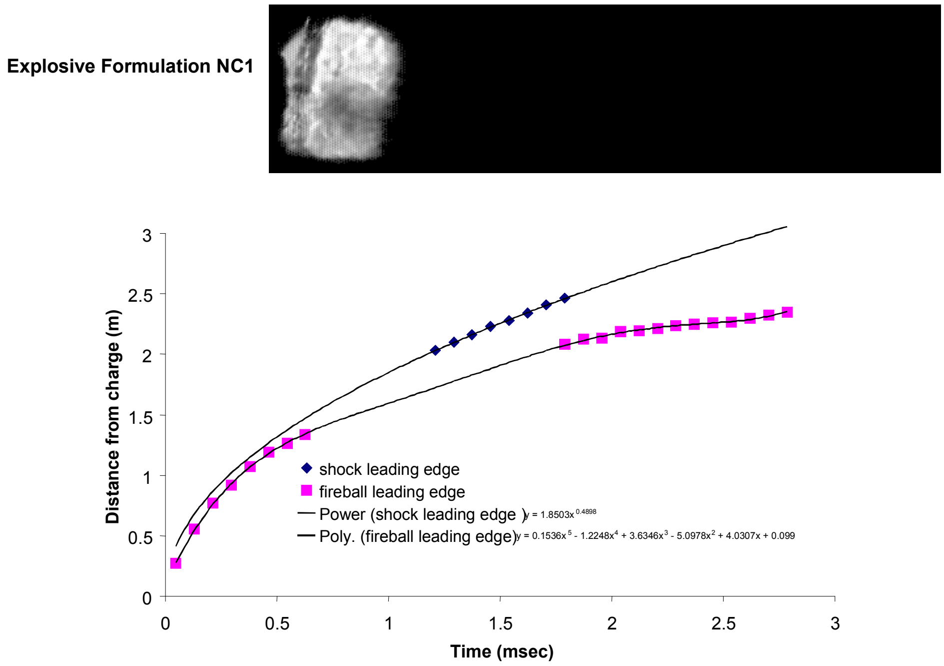

Figure 6: HBI imaging data from measurements of explosive formulation NC1, showing shock and fireball leading edges as a function of time after initiation. Also shown in inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

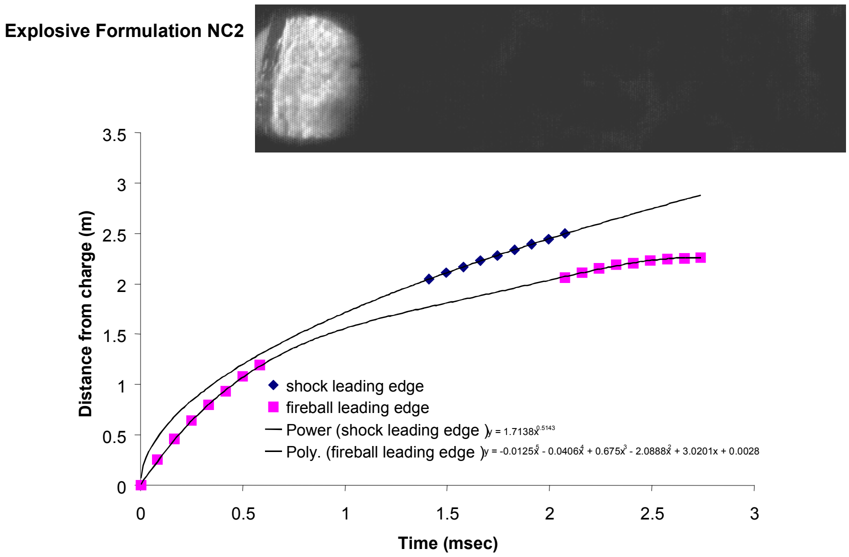

Figure 7: HBI imaging data from measurements of explosive formulation NC2, showing shock and fireball leading edges as a function of time after initiation. Also shown in inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

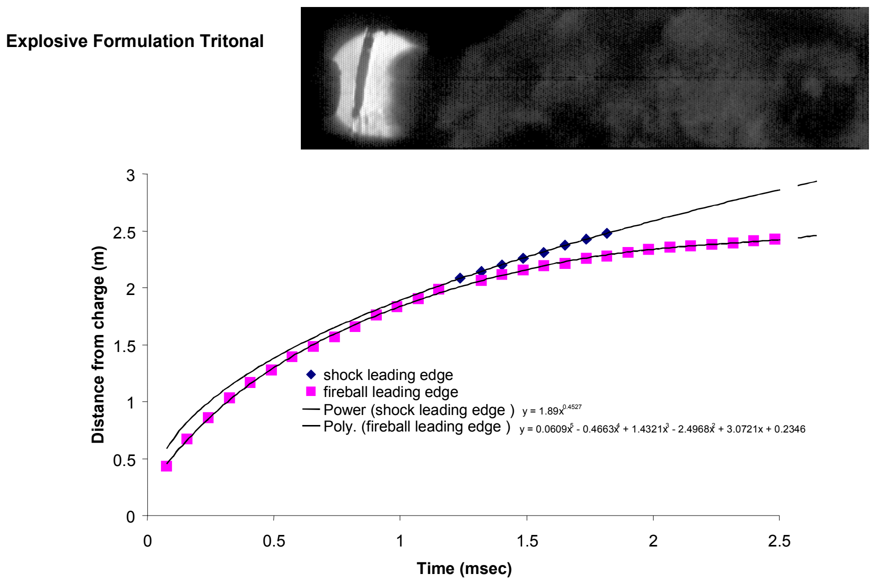

Figure 8: HBI imaging data from measurements of explosive formulation Tritonal, showing shock and fireball leading edges as a function of time after initiation. Also shown in inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

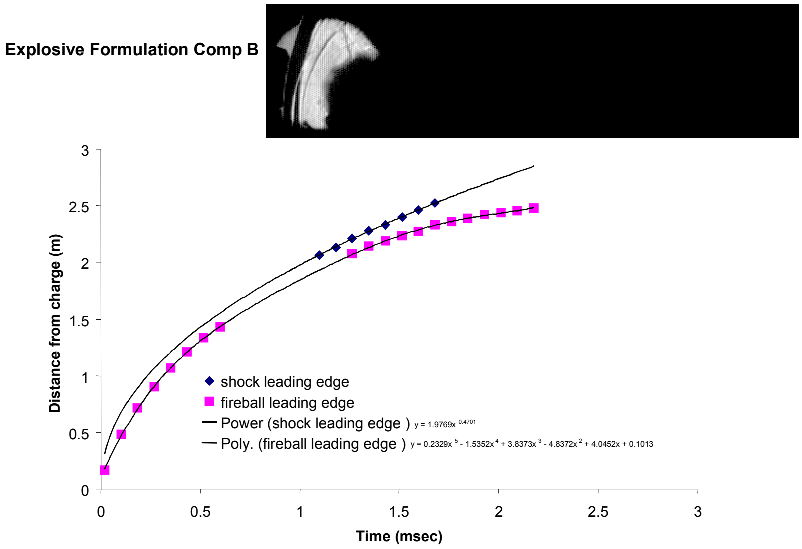

Figure 9: HBI imaging data from measurements of explosive formulation Comp B, showing shock and fireball leading edges as a function of time after initiation. Also shown in inset is an image of the leading shock and following fireball edge passing through the laser-illuminated region. Shock data (diamonds) and fireball leading edge data (rectangles) have best fit trend lines drawn through each point as an aid to the eye. Note separation distance between shock and fireball edges versus time.

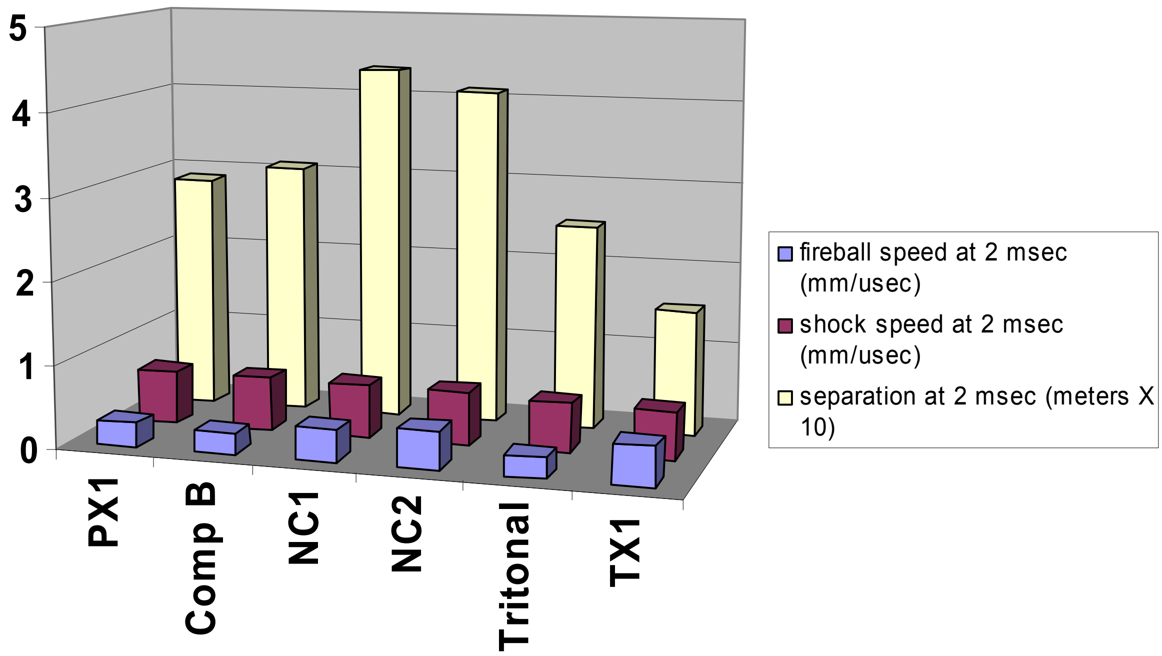

Figure 10: A summary of the data for the 6 explosive formulations tested. Note the increase in fireball speed and in fireball and shock edge separation for explosive formulations NC1 and NC2.